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Progressive Retry for Software Error Recovery in Distributed Systems

Yi-Min Wang
Coordinated Science Laboratory
University of Illinois
Urbana, IL 61801

Yennun Huang
AT&T Bell Laboratories
Murray Hill, NJ 07974

W. Kent Fuchs
Coordinated Science Laboratory
University of Illinois
Urbana, IL 61801

Abstract

In this paper, we describe a method of execution retry for bypassing software faults based on checkpointing, rollback, message reordering and replaying. We demonstrate how rollback techniques, previously developed for transient hardware failure recovery, can also be used to recover from software errors by exploiting message reordering to bypass software faults. Our approach intentionally increases the degree of nondeterminism and the scope of rollback when a previous retry fails. Examples from our experience with telecommunications software systems illustrate the benefits of the scheme.

1 Introduction

Numerous checkpointing and rollback recovery techniques have been proposed in the literature to recover from transient hardware failures. *Uncoordinated checkpointing* schemes [1, 2] allow maximum process autonomy and general nondeterministic execution, but suffer from potential domino effects [3]. *Coordinated checkpointing* schemes [4, 5] eliminate the domino effect by sacrificing a certain degree of process autonomy and by paying the cost of extra coordination messages. Recently, a *lazy checkpoint coordination* technique [6] has been proposed as a mechanism for bounding rollback propagation and providing a flexible trade-off between run-time coordination overhead and recovery efficiency.

Log-based recovery provides another way of achieving domino-free recovery. Under the *piecewise deterministic model* [7], the domino effect is avoided through message logging and deterministic replaying. In a *pessimistic logging protocol* [8, 9], each message is logged upon receipt which prevents the rollback of a faulty process from causing the rollback of any other process. *Optimistic logging protocols* [10–12] have been proposed to reduce run-time overhead by using asynchronous message logging at the expense of possible rollback propagation due to lost volatile message logs upon failure.

Instead of proposing another checkpointing and recovery protocol, this paper investigates the possibility of applying the log-based techniques to recovery from software errors [10, 13–16]. We previously proposed message reordering for changing the communication pattern at run-time in order to reduce the rollback distance for *hardware failures* [17]. In this paper, we demonstrate how message reordering can also provide an effective way of bypassing certain *software faults*. Fig. 1 illustrates the basic concept. When a software error is detected at the point marked "X", rollback and message replaying based on the complete checkpoint and message log information may lead to the same error. By intentionally discarding part of the message logs, we can deterministically reconstruct the system state up to the dotted line shown in Fig. 1, and then use message reordering to introduce nondeterministic execution beyond the dotted line in order to bypass the software fault. Unlike the recovery block approach [3] and N-version programming [18] which both use *different programs* to execute on the same set of data, the above on-line retry approach [14, 19] uses the same program to operate on a *different but consistent set of data* [20] obtained through message reordering.

Based on our experience with telecommunications software systems, the technique of execution retry with rollback and message replaying has demonstrated its usefulness for bypassing the so-called *software boundary errors*. Usually, an application contains a main routine that performs the designated functions, and some *boundary code* for handling specific situations, collectively referred to as *boundary conditions*, such as program exceptions, resource failures, urgent or unexpected messages, failures on system or function calls, etc. The boundary code is often not well tested due to the difficulty in creating such boundary conditions in a test environment [15]. It has been shown that the

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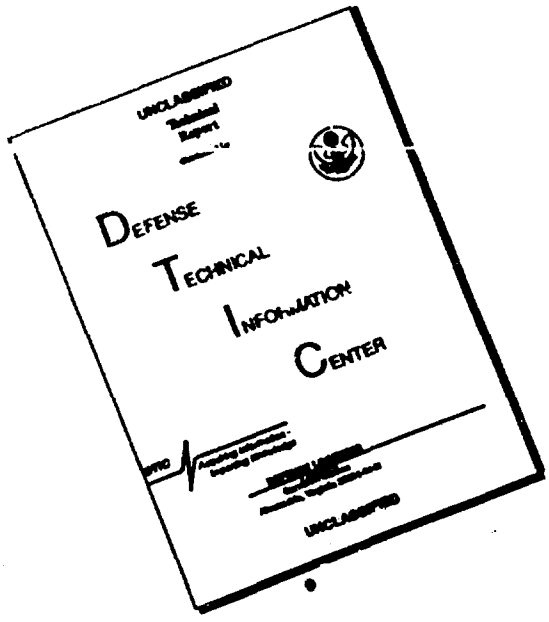

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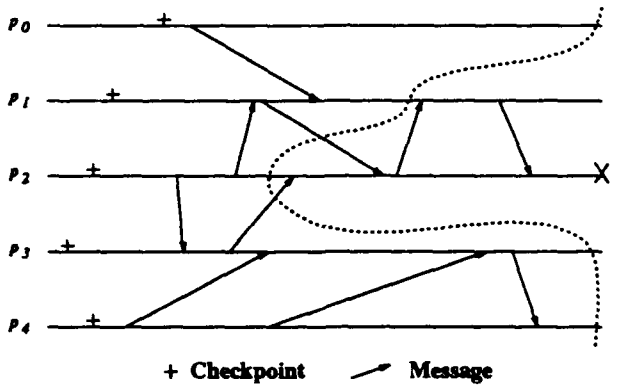

Figure 1: Nondeterministic execution through message reordering.

possibility of software errors in the boundary code, called *software boundary errors*, can be significantly higher than that in the main routine [15]. These kinds of software boundary errors may cause a catastrophic event such as the AT&T 4ESS switching system failure in January 1990 [21]. The fact that a software boundary condition usually occurs very rarely also suggests that if a boundary error does occur, then on-line retry by replaying and/or reordering the incoming messages may be helpful in bypassing the boundary condition.

The simplest approach to execution retry is to roll back the entire system and restart from a consistent global checkpoint. This can result in nondeterministic execution in a distributed message-passing environment and this nondeterminism may result in bypassing the boundary condition. However, it is often desirable to limit the scope of rollback, the number of involved processes as well as total rollback distance, in order to achieve faster recovery [22]. It is possible that a small-scope rollback involving only a few processes suffices for successful retry. This motivates the *progressive retry* concept which progressively increases the scope of rollback to intentionally introduce more nondeterminism when a previous retry fails. Such an idea has been implemented in a telecommunication billing system and has been shown to improve the availability of the systems. The objective of this paper is to describe and formalize the concept of progressive retry with message reordering to bypass software errors and to present a framework for implementation. The technique is being built into an existing fault tolerance library [23] in order to facilitate future software development.

2 Logical Checkpoints and Recovery Lines

Let N be the number of processes in the system. Suppose p_1 in Fig. 2 initiates a rollback at the point marked "X". In a general nondeterministic execution, the rollback of p_1 to its checkpoint C will *unsend* messages M_1 and M_3, and thus require p_0 to roll back to a state before the receipt of M_1 in order to *unreceive* M_1 and similarly require p_2 to *unreceive* M_3; otherwise, M_1 and M_3 are recorded as "received but not yet sent", which results in an inconsistency of system state.

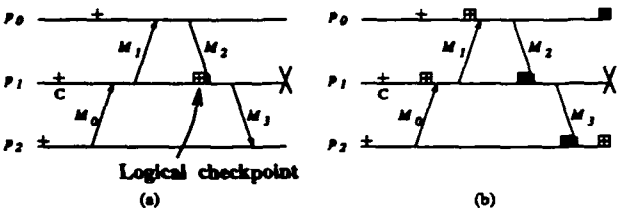

Figure 2: State consistency (a) example checkpoint and communication pattern, (b) logical checkpoint dependency and recovery line.

However, if p_1 can reconstruct the state from which M_1 was generated[2], the execution of p_0 based on the processing of M_1 is still valid and therefore p_0 need not roll back. This can be achieved by the *piecewise deterministic model* and additional message logging and replaying. The piecewise deterministic model says: process execution between two consecutive message receipts, called a *state interval*, is deterministic. So if p_1 has logged both the message content and the *state interval index* [11] (i.e., the processing order) for message M_0 (but not for M_2) by the time it initiates the rollback, p_1 can deterministically reconstruct the state up to immediately before the receipt of M_2 (a nondeterministic event) and therefore M_1 remains a valid message.

A useful way to unify these two seemingly different state consistency concepts is to introduce the notion of a logical checkpoint. While a *physical checkpoint* like checkpoint C allows the restoration of process state at the point the checkpoint was taken, checkpoint C and the message log of M_0, plus the underlying piecewise deterministic model effectively place a *logical checkpoint* at the end of the state interval started by M_0 (as shown in Fig. 2(a)) because of the capability of state reconstruction. In other words, although p_1 "physically" rolls back to checkpoint C, it "logically" rolls back to the above logical checkpoint and therefore does not *unsend* M_1. It then becomes clear that while

[2]Here we assume fail-stop [24] failures only for the purpose of introducing logical checkpoints. The Step 4 and Step 5 in our progressive retry technique described in the next section can in fact relax such an assumption.

"physical rollback distance" determines the rollback extent of each individual process, "logical rollback distance" controls the extent of rollback propagation and therefore the number of processes involved in the recovery. For simplicity, we let each physical checkpoint initiate a new state interval and represent it by a logical checkpoint at the end of that interval. Based on the above notion of logical checkpoints, the following *rollback propagation rule*[3] is then valid with or without the piecewise deterministic model:

> **if the sender (logically) rolls back and *unsends* a message M, the receiver must also (logically) roll back to *unreceive* M.**

We define a *global checkpoint* as a set of N (logical) checkpoints, one from each process. A *consistent global checkpoint* is a global checkpoint that does not contain any two checkpoints violating the above rollback propagation rule. The *recovery line* is the latest available consistent global checkpoint which uniquely minimizes the total rollback distance [25]. As an illustration, suppose all the messages in Fig. 2(a) except for M_2 are logged when p_1 initiates the rollback. Fig. 2(b) shows the dependency graph for the available logical checkpoints. By starting with the set of the last logical checkpoints of each process and applying the rollback propagation rule described above, we can determine the recovery line to be the set of shaded checkpoints in Fig. 2(b). Notice that p_0 may be required to physically roll back in order to regenerate the lost message M_2.

3 Progressive Retry for Bypassing Software Errors

We base our discussion on the following system model and recovery protocol.

FIFO channel: messages sent along the same channel between any two processes are ordered by monotonically increasing *sequence numbers*.

Merge component: messages from all incoming channels are merged by the merge component [10] based on a changeable merge function, and are assigned the state interval indices.

Logging before processing: every message is logged before delivery to the application process[4].

Direct dependency tracking [11, 25, 26]: only the dependency of the receiver's logical checkpoint on the sender's logical checkpoint resulting from each message processing is recorded, as opposed to the *transitive dependency tracking* which has been used in many log-based papers [10, 12].

Centralized recovery line computation: the global dependency information is collected by the process which initiates the garbage collection or recovery procedure [2, 11] and is responsible for the recovery line computation[5].

3.1 Recovery Line and Message Logs

With respect to the recovery line consisting of the shaded checkpoints shown in Fig. 3, messages can be classified into four categories.

1. **Obsolete messages:** In order to reconstruct the state up to the recovery line, the system can restart from the set of *restarting checkpoints*, called the *restart line*, as illustrated in Fig. 3. Messages that were processed before the restart line, for example, M_O, are therefore obsolete messages and not useful for recovery.

2. **Messages for deterministic replay (deterministic messages):** Messages processed between the restart line and the recovery line must have both their message contents and state interval indices logged. These messages need to be replayed in their original order for deterministic state reconstruction. M_D and M'_D are such messages.

3. **In-transit (or channel-state) messages:** For messages sent before the recovery line and processed after, only the message contents in the log are valid. The state interval indices are either not logged or invalidated. Messages like M_I and M'_I belong to this category and can be processed in arbitrary order.

4. **Orphan messages:** Messages sent after the recovery line are orphan messages. M'_R can not exist because otherwise the recovery line is not consistent. M_R is invalidated by the rollback and should be discarded.

In an optimistic logging protocol [10], rollback propagation can result from the nondeterminism due to lost volatile message logs upon failure. Based on the available message logs from stable storage, the recovery line is uniquely determined and each message must statically belong to one of the four categories depending on its position relative to the

[3] In contrast, when the receiver (logically) rolls back and *unreceives* a message M', the sender does not have to (logically) roll back if M' is logged at the sender or the receiver side and can be retrieved during reexecution, or if M' can be regenerated by the sender.

[4] The results can be extended to systems with asynchronous (optimistic) message logging by making additional logical checkpoints unavailable for those volatile message logs lost due to the failure.

[5] A distributed and synchronized algorithm has been proposed by Sistla and Welch [12]. A distributed and asynchronous algorithm can be found in Strom and Yemini's paper [10].

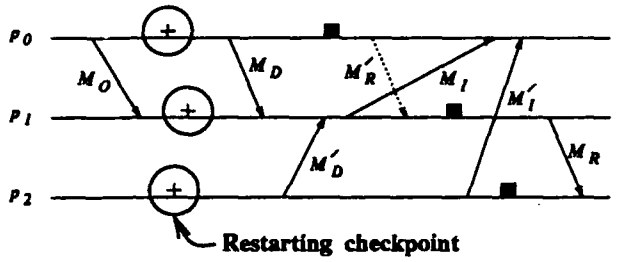

Figure 3: Example of obsolete, deterministic, in-transit and orphan messages.

recovery line. In contrast, our retry technique progressively increases the degree of nondeterminism and the scope of rollback by discarding more message logs as a previous retry fails. At each step, a new recovery line or restart line is computed based on the remaining checkpoint and message log information. Since the recovery line moves backward in time during the progressive retry, messages belonging to the ith category can shift to the jth category, where $4 \geq j \geq i \geq 1$, at a later stage.

4 Progressive Retry

We will use the example checkpoint and communication pattern shown in Fig. 4 to illustrate progressive retry in five steps.

Step 1 - Receiver deterministic retry: When p_2 detects an error, it first initiates a local recovery by rolling back to checkpoint C and deterministically replaying the message logs. Because every message is logged before processing, message logs for M_a, M_b and M_c must be available and allow p_2 to reconstruct the state up to the point it detected the error, as illustrated by the recovery line shown in Fig. 4(a). In some cases, transient failures may be caused by some environmental factors which will simply disappear after the recovery, and the Step-1 retry may succeed. If the reexecution still leads to the same error, the checkpoint and message log information is copied to a trace file for off-line debugging and Step 2 is initiated.

Step 2 - Receiver nondeterministic retry: p_2 starts introducing nondeterminism by discarding the state interval indices of M_a, M_b and M_c in order to allow message reordering. As a result, the last three logical checkpoints of p_2 are now unavailable and the resulting recovery line is shown in Fig. 4(b). Notice that only M_a and M_b are in-transit messages available for reordering; message M_c as well as M_g now become orphan messages and should be discarded.

Message reordering can be achieved by random reordering or by restoring the in-transit messages to the input of the merge component and re-assigning them with possibly different state interval indices. An alternative is to group the messages from the same process together if the software bug is possibly due to the interleaving of messages from different processes. If only two messages are involved, forcing them into the opposite order may be useful.

Step 3 - Sender deterministic retry: The main purpose of this step is to include more "future" messages for reordering in order to increase the effectiveness. It is useful, for example, when a software fault is triggered by some unexpected delay in the delivery of certain messages.

Messages that have arrived at the receiver but not yet been logged can be lost upon failure. Message M_d in Fig. 4 is an example. Such lost messages can be detected[6] when the receiver receives another message from the same sender which indicates a discontinuity in the message sequence number [10]. The sender is then requested to resend the message if sender logging is available [10], or to regenerate the message through deterministic state reconstruction [12].

The immediate recovery of such lost messages is useful for increasing the number of messages available for reordering. p_2 now discards the message contents of M_a and M_b as well. Although the resulting recovery line as shown in Fig. 4(c) is the same as the one in (b), p_3 in addition to p_1 and p_2 is rolled back[7] in order to regenerate (recover) the lost message M_d.

Step 4 - Sender nondeterministic retry: When reordering M_a, M_b, M_d and possibly other recently arrived non-orphan messages still fails to bypass the software fault, p_2 suspects some of these messages should not have been generated in the first place. Therefore, p_1 and p_3 are requested to roll back further by discarding the state interval indices of the message logs that can deterministically generate these messages. The resulting recovery line is given in Fig. 4(d). Nondeterminism can be introduced by p_1 reordering M_v and M_w, and p_3 reordering M_x, M_y and M_z.

Step 5 - Large-scope rollback retry: When all previous small-scope retries fail, a large-scope rollback can be

[6] For some applications, lost messages may be acceptable. For example, if the lost message is a channel request message in a telephone switching application, the user will simply redial or try again later.

[7] p_2 can notify p_3 to roll back by sending p_3 the largest sequence number of any message sent from p_3 and received by p_2 before checkpoint C. Similar messages are sent to all other processes.

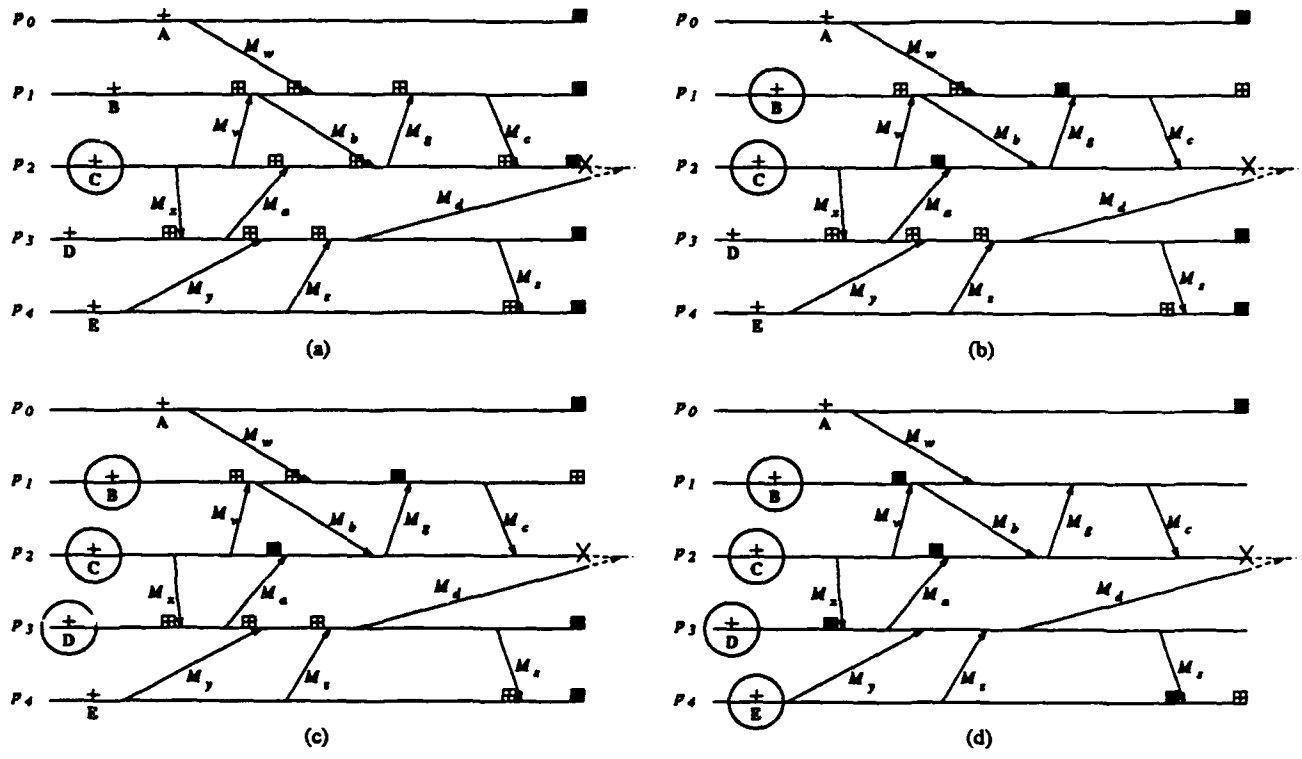

Figure 4: Progressive retry (a) Step 1: receiver deterministic retry (b) Step 2: receiver nondeterministic retry (c) Step 3: sender deterministic retry (d) Step 4: sender nondeterministic retry.

initiated. Instead of backing off a few state intervals for reordering a small number of messages involving a small number of processes, all processes in the system are requested to roll back K intervals where K should be a large number compared to the distances involved in Step 1 through Step 4. The recovery line computed from the remaining available logical checkpoints is then used for the final-step retry.

The choice of K is a trade-off between output commit and garbage collection versus the available nondeterminism. Outputs to the outside world that cannot be rolled back should only be released after the recovery line has advanced beyond the state intervals that generate these outputs. Checkpoints and message logs can only be garbage-collected after the restart line has passed their corresponding state intervals [12]. Therefore, while a larger K means more nondeterminism is available, it also results in slower output commit and less effective garbage collection, which are translated into slower response to the users and larger space overhead, respectively. In the extreme case where fast output commit is the most important requirement for the system, only those state intervals beyond the last output can be backed off for introducing nondeterminism [10].

5 Experience and Discussion

In this section, we describe two examples from telecommunications software with software boundary errors. By using the progressive retry technique (Step 1 for Case 1 and Step 3 for Case 2), these programs were able to quickly recover from the errors without service interruption. To simplify the description, we have abstracted only the components which contributed to the errors.

Case 1

A telecommunication billing system consists of several processes using shared memory for interprocess communication. There is one writer process which updates several data structures in the shared memory and the others are reader processes which read these data structures. Because no semaphore or locking mechanism is used in accessing the shared memory, there is a small probability that a reader may be accessing the data structure while the writer is updating it (e.g., manipulating the pointers for inserting a new

data node). In such a case, the reader receives a segmentation violation fault and is then recovered by a watcher process. Once the reader is restarted and tries to read the same data structure again, the read operation succeeds because the writer has finished the update.

This kind of error occurs once every few days. Whenever it happens, the Step 1 retry mechanism can quickly correct the error. An alternative (standard) way of dealing with this problem would be to use a locking mechanism for accessing the shared memory. However, using coarse-grain locks can result in unnecessary blocking of the reader processes, and using fine-grain locks will incur large performance degradation and introduce additional software complexity. Therefore, the billing system has relied on the progressive retry mechanism as an alternative to a locking mechanism to deal with the concurrency problem. The approach is feasible in this case because mutual-exclusive conflict only occurs rarely and it is detected when it does occur.

Case 2

In a cross-connection system, a *Channel Control Monitor* (CCM) process is used to track the available channels in the switch. The CCM process receives information from two other processes: a *Channel Allocation* (CA) process which sends the channel allocation requests and a *Channel Deallocation* (CD) process which sends the channel deallocation requests. A boundary condition for CCM occurs when all channels are used and the process receives additional allocation requests. In that case, a clean-up procedure is called to free up some channels or to block further requests. However, the clean-up procedure contained a software fault which could cause the process to crash.

The cross-connection system uses a daemon watcher to detect a process failure and employs a checkpointing and message logging mechanism to recover from the failure. The following example illustrates how progressive retry works in this system. Suppose the number of available channels is 5. The command `r2` stands for requesting two channels, and the command `f2` stands for freeing two channels. The following command sequence could cause the CCM process to crash because of the boundary error.

```
CA sends r2 r3 r1
CD sends f2 f3 f1
CCM receives r2 r3 r1 and crash
```

If the message `f2` is received and logged before CCM crashes, CCM will be able to recover by reordering the message logs. However, if CCM crashes before the `f2` message is logged, reordering messages `r2`, `r3` and `r1` (Step 2) will not help. In this case, the local recovery of CCM fails and CA and CD will be requested to resend their messages (Step 3). Because of the nondeterminism in operating system scheduling and communication delay, the messages may arrive at CCM in a different order. For example, the message order can be

```
r2 r3 f2 f3 r1 f1
```

Since the boundary error does not occur in this case, the progressive retry involving three processes succeeds.

6 Concluding Remarks

We have described a method of applying the log-based recovery technique, previously developed for fail-stop hardware failures, to recovery from transient software errors. Our five-step progressive retry approach discards partial message log information at each step in order to introduce an increasing degree of nondeterminism for bypassing software faults. Although not every software error can be recovered through message resending, reordering and replaying, we have observed that progressive retry can provide an effective and economic way of recovering from boundary errors in long-life software systems. For a specific telecommunication billing system, all the software errors occurring for the past two years have been automatically corrected by either Step 1 or Step 3 of the progressive retry mechanism. For a replicated file system, we have observed that Step 1 and Step 2 were able to recover from 90% of the software errors for the past six months.

The techniques described are being implemented in the fault tolerance library `libft` which has been developed at AT&T Bell Laboratories [23]. `Libft` is a C library which supports N-version programming, recovery blocks, exception handling, message logging, and checkpointing and rollback recovery, and has been used by several AT&T products. Currently, the recovery mechanism in `libft` provides the first two steps of progressive retry, with the implementation of the remaining steps in progress and the investigation of other useful reordering algorithms as an important topic for future research.

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